

# Stability of Full Penetration, Flat Position Weld Pools

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**ABSTRACT.** The dynamics of the droptthrough distance of a full penetration, flat position weld pool is described. Close to incipient root side penetration the droptthrough is metastable, so that a small drop in power can cause a loss of penetration if not followed soon enough by a compensating rise in power. The SPA process with higher pressure on top of the weld pool loses penetration more quickly than the GTA process. 2195 aluminum-lithium alloy with a lower surface tension loses penetration more quickly than 2219 aluminum alloy. An instance of loss of penetration of a SPA weld in 2195 aluminum-lithium alloy is discussed in the light of the model.

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## Introduction

If full penetration is not maintained in the root pass of a weld, a lack-of-penetration defect is left behind and must be fixed. This study was motivated by a need to understand and avoid the occurrence of occasional sudden, unexplained losses in penetration during flat position Soft Plasma Arc (SPA) welding of 2195 aluminum-lithium alloy.

The SPA process is an adaptation of the Variable Polarity Plasma Arc (VPPA) welding process. The plasma gas flow rate is reduced for the SPA process so as to reduce the stagnation pressure and penetration of the plasma jet below that of the VPPA process. While the penetration of the VPPA plasma jet through the workpiece in the "keyholing" mode of operation is a desirable feature in that it flushes the weld and acts to prevent porosity [1], when backshielding is necessary, as is the case for aluminum-lithium alloys, the interaction of plasma gas with the backshield gas causes pool stability problems. The SPA plasma jet does not penetrate the workpiece in the keyhole mode. Nevertheless, the SPA weld pool can still penetrate deeper for a given width than a Gas Tungsten Arc (GTA) weld.

The liquid metal of a fully penetrating weld pool in the flat position is held in place by the surface tension of the liquid on the root surface of the pool. The weight of the metal in the pool forces the metal down against the liquid metal skin at its root. So does any pressure on the top of the weld pool. More power will extend the melting isotherm of the pool boundary and widen the root surface holding up the pool; this will cause the distance between the plate bottom and the bottom of the pool root bulge, which will be referred to as the "droptthrough" distance, to increase.

It is possible to write a differential equation for the rate of change of droptthrough. There is feedback in the equation for the dynamics of the droptthrough. If plasma torch is locked in place with respect to the upper surface of the plate, a decrease in droptthrough not only raises the level of upper surface of the pool, but incidentally shortens the plasma arc and reduces the arc voltage and power input to the pool. Further, if there is pressure on the top of the pool surface, only that pressure directly over the root is counterbalanced by the surface tension. If the pressure is flatly distributed, the pressure force on the root area causing droptthrough is proportional to the square of the radius of the root area radius. Both power and pressure force drop off if a small power fluctuation causes the weld pool to shrink. Thus power fluctuations either up or down are amplified within the welding system. According to the model the SPA process with its higher pressure atop the weld

should be less stable with respect to sudden loss of penetration than the GTA process, and it was with the SPA process that the sudden penetration loss problem surfaced.

Further, the metal characteristics also have an effect. According to the model a low surface tension makes a metal less stable with respect to loss of penetration. Welders report that the sudden penetration losses encountered by 2195 aluminum-lithium alloy are not encountered with 2219 aluminum alloy. According to theory the critical metal characteristic is the surface tension. Weld metals also have different tendencies to evaporate depending on alloying constituents and one might expect this to exert some pressure on the weld top surface, but a rough estimate of the order of magnitude of such pressures yields values below 0.005 psi, hence this effect is taken to be negligible.

Some preliminary attempts to measure surface tension from weld pool droptthrough were made by Talia and Nunes [2]. The surface tensions measured were 940 dynes/cm (standard deviation =74) for 2195 aluminum-lithium alloy and 1094 dynes/cm (standard deviation =104) for 2219 aluminum alloy.

## Droptthrough Dynamics

Droptthrough dynamics is taken to depend upon a heat balance at the weld pool surface [3]:

$$\rho L_m \frac{dV}{dt} = P_{in} - P_{out} \quad (1)$$

where  $V$  = weld pool volume

$L_m$  = latent heat of melting of the weld pool metal

$\rho$  = density of the weld pool metal

$P_{in}$  = power input to pool

$P_{out}$  = power loss from pool.

The heat absorbed in melting a volume  $dV$  of metal at the edge of the pool is equated to the difference between the energy fed to the pool  $P_{in} dt$  by the plasma above the pool and that lost by conduction  $P_{out} dt$  into the workpiece. The velocity of the weld is assumed slow and to have minimal effect on the dynamics considered here and a quasi-static situation is assumed.

Given a point heat source  $P_{in}$  in equilibrium (so that  $P_{in} = P_{out} = P$ ) in a homogeneous, isotropic space that conducts heat with thermal conductivity  $k$ , the isotherm at temperature  $T_m$  is located at radius  $r$  from the heat source.

$$r = \frac{P}{2\pi k(T_m - T_o)} \quad (2)$$

where  $T_m$  = temperature of isotherm of space

$T_o$  = ambient temperature of space

$k$  = thermal conductivity of space

$r$  = radius of isotherm at  $T_m$  from point heat source.

The isotherm can be an approximate representation of the boundary of a relatively shallow weld pool reduced on the surface of a very large block of weld metal if  $P_{in} = P_{out}$  is the weld power delivered to the block surface. The approximation is crude, but the main concern here is with the effect of the bottom of the plate.

A plate with a bottom can be approximated by linear array of point sources [4] spaced at twice the thickness of the plate. Two planes of symmetry perpendicular to the

linear array model the plate surfaces. One surface has no heat crossing it (by symmetry) and represents the bottom of the plate. Another surface has no heat crossing it except at a heat source singularity. This represents the top of the plate and the welding heat source. The crown width at the top of the plate in this approximation is

$$\frac{r_c}{w} = \frac{p}{2\pi kw(T_m - T_o)} \left\{ 1 + \sum_{n=1}^{\infty} \frac{2}{\sqrt{1 + (2n)^2 \left(\frac{w}{r_c}\right)^2}} \right\} \quad (3)$$

where  $r_c$  = crown radius of weld pool  
 $w$  = plate thickness.

The root width at the bottom of the plate is likewise

$$\frac{r_r}{w} = \frac{p}{2\pi kw(T_m - T_o)} \left\{ \sum_{n=0}^{\infty} \frac{2}{\sqrt{1 + (1 + 2n)^2 \left(\frac{w}{r_r}\right)^2}} \right\} \quad (4)$$

where  $r_r$  = root radius of weld pool.

Neither of these sums can be evaluated as they do not converge, however, it must be remembered that there are no infinite dimensions in the situation we are attempting to model. So we shall be very crude and approximate the effect of a plate bottom ignoring sources at a distance  $3w$  or greater from the location of interest. Thus three sources are used to determine the crown radius and two to determine the root radius.

$$\frac{r_c}{w} \sim \frac{P}{2\pi kw(T_m - T_o)} \left[ 1 + \frac{1}{\sqrt{\frac{1}{4} + \left(\frac{w}{r_c}\right)^2}} \right] \quad (5)$$

$$\frac{r_r}{w} \sim \sqrt{4 \left( \frac{P}{2\pi kw(T_m - T_o)} \right)^2 - 1} \quad (6)$$

If the weld fusion zone shape is approximated by an ellipse

$$\frac{r}{r_c} \approx \sqrt{1 - \left(\frac{z}{w+x}\right)^2} \quad \text{for} \quad x \leq 0 \quad (7a)$$

$$\frac{r}{r_c} \approx \sqrt{1 - \left(\frac{z}{w}\right)^2 \left[1 - \left(\frac{r_r}{r_c}\right)^2\right]} \quad \text{for} \quad x \geq 0 \quad (7b)$$

where  $z$  = the depth into the plate from the crown surface,

then the volume  $V$  of the pool can be approximated:

$$V \approx \frac{2\pi r_c^2 w}{3} \left(1 + \frac{x}{w}\right) \quad \text{for} \quad x \leq 0 \quad (8a)$$

$$V \approx \frac{2\pi r_c^2 w}{3} \left[1 + \frac{1}{2} \left(\frac{r_r}{r_c}\right)^2\right] \quad \text{for} \quad x \geq 0 \quad (8b)$$

The top and bottom of the weld pool each comprise a meniscus. The depression of the top meniscus is  $s$ ; that of the bottom, the droptrough, is  $x$ . The menisci are approximated by spherical surfaces.

They exert surface tension forces that hold up the column of liquid over the root penetration area  $\pi r_r^2$ , or, if one is particular, to the forward half of the column, the back half being held up by prow of the solidified root bead. The force balance on this column can be written

$$2\pi r_r \gamma \left\{ \frac{2x r_r}{x^2 + r_r^2} + \frac{2\Delta s r_r}{\Delta s^2 + r_r^2} \right\} \approx \rho g \left\{ \frac{\pi}{6} r_r^2 x \left[ 1 + 3 \left( \frac{x}{r_r} \right)^2 \right] + \pi r_r^2 (w - s) + \pi r_r^2 \Delta s \left[ 1 - \frac{1}{6} \left[ 1 + \left( \frac{\Delta s}{r_r} \right)^2 \right] \right] \right\} + \Phi \pi r_r^2 \quad (9)$$

where  $\gamma$  = surface tension  
 $x$  = droptrough depression at weld root  
 $\rho$  = weld pool density  
 $g$  = acceleration of gravity

$\Phi$  = pressure on weld crown

$\Delta s$  = depression of top meniscus with respect to  $r$ , surface radius

$$\frac{\Delta s}{s} = \frac{\left(\frac{r_r}{s}\right)^2}{1 + \left(\frac{r_c}{s}\right)^2} \approx \left(\frac{r_r}{r_c}\right)^2 \quad (10)$$

$s$  = total depression of meniscus at weld pool crown

The volume inside the root meniscus is  $\frac{\pi}{6} r_r^2 x \left[ 1 + \left(\frac{x}{r_r}\right)^2 \right]$ . The volume inside the crown meniscus is  $\frac{\pi}{6} r_c^2 s \left[ 1 + \left(\frac{s}{r_c}\right)^2 \right] \approx \frac{\pi}{6} r_c^2 s$  when  $s \ll r_c$ . If the volume change due to melting is neglected, these two volumes are equal for a stationary pool. For a stationary pool with wire feed the volume increases without limit. For a moving weld pool the volume increases by the amount of influx during the transient establishment of steady flow, about the time for the pool to move one crown diameter.

$$\frac{\pi}{6} r_r^2 x \left[ 1 + \left(\frac{x}{r_r}\right)^2 \right] - \frac{\pi}{6} r_c^2 s \left[ 1 + \left(\frac{s}{r_c}\right)^2 \right] \approx a_w v_w \left(\frac{2r_c}{v}\right) \quad (11)$$

Hence assuming  $s \ll r_c$ ,

$$s \approx x \left(\frac{r_r}{r_c}\right)^2 \left[ 1 + \left(\frac{x}{r_r}\right)^2 \right] - \frac{12 a_w v_w}{\pi r_c v} \quad (12)$$

where  $a_w$  = weld wire cross sectional area  
 $v_w$  = weld wire feed rate

If  $\Delta s \ll s \ll x \ll r_r$ , then force equilibrium on the pool relates droptrough to pool root width

$$\frac{x}{w} \approx \left\{ \frac{\frac{\rho g w^2}{4\gamma} \left(1 - \frac{s}{w}\right) + \frac{\Phi w}{4\gamma}}{1 - \frac{\rho g w^2}{4\gamma} \left(\frac{r_r}{w}\right)^2} \right\} \left(\frac{r_r}{w}\right)^2 \quad (13a)$$

and, eliminating the  $\frac{s}{w}$  term,

$$\frac{x}{w} \approx \left\{ \frac{\frac{\rho g w^2}{4\gamma} \left( 1 + \frac{12 a_w v_w}{\pi r_c v} \right) + \frac{\Phi w}{4\gamma}}{1 - \frac{\rho g w^2}{4\gamma} \left( \frac{r_r}{w} \right)^2 \left[ 1 - \left( \frac{r_r}{r_c} \right)^2 \right]} \right\} \left( \frac{r_r}{w} \right)^2 \quad (13b)$$

At conditions close enough to loss of penetration where  $r_r \ll w$  and  $r_r \ll r_c$

$$\frac{x}{w} \sim \frac{\rho g w^2}{4\gamma} \left( 1 + \frac{12 a_w v_w}{\pi r_c v} + \frac{\Phi}{\rho g w} \right) \left( \frac{r_r}{w} \right)^2 = \Gamma^2 \left( \frac{r_r}{w} \right)^2 \quad (13c)$$

where  $\Gamma \equiv \sqrt{\frac{\rho g w^2}{4\gamma} \left( 1 + \frac{12 a_w v_w}{\pi r_c v} + \frac{\Phi}{\rho g w} \right)}$

From equations (5) and (6)

$$\frac{d\left(\frac{r_c}{w}\right)}{d\left(\frac{r_r}{w}\right)} \sim \left\{ \frac{4\left(\frac{r_r}{w}\right)}{\sqrt{\left(\frac{r_r}{w}\right)^2 + 1}} \right\} \left\{ \frac{\sqrt{\frac{1}{4} + \left(\frac{w}{r_c}\right)^2}}{\sqrt{\frac{1}{4} + \left(\frac{w}{r_c}\right)^2} + \frac{1}{\left(\frac{r_c}{w}\right)^2 \left[ \sqrt{\frac{1}{4} + \left(\frac{w}{r_c}\right)^2} + 1 \right] \left[ \frac{1}{4} + \left(\frac{w}{r_c}\right)^2 \right]^{\frac{3}{2}}}} \right\} \quad (14)$$

At conditions of incipient loss of penetration where  $\frac{r_c}{w} \sim 1$  and  $\frac{r_r}{w} \sim 0$   $r_c$  can be taken as a constant since, according to equation (14)  $\frac{dr_c}{dr_r} \sim 0$ . That is, while the crown

width is not very sensitive to a small fluctuation in power and remains about the same, small fluctuations in power may cause relatively large variations in the root width. Welders know that it is hard to maintain conditions of incipient penetration. Running with a relatively large root width tends to prevent loss of penetration, but with too wide a root bead the pool can drop out. Pool dropout occurs at  $x \approx r_r$  (a hemispherical droptrough configuration), so for a stable pool

$$\frac{r_r}{w} < \frac{1}{\Gamma^2} \quad (15)$$

Factors that cause dropout of the pool are seen to be metal density, plate thickness, wire feed, and pressure over the pool crown. The higher the surface tension of the pool metal, the wider the root that can be maintained.

If equations (8b) and (13c) are incorporated into equation (1), an equation for the dynamics of the droptrough where  $\frac{r_c}{w}$  is constant and  $\frac{r_r}{w} \sim 0$  so that  $\left(\frac{r_r}{w}\right)^2 \ll \left(\frac{r_r}{w}\right)$  is obtained.

$$\rho L_m \frac{d}{dt} \left\{ \frac{2\pi r_c^2 w}{3} \left[ 1 + \frac{1}{2} \left( \frac{w}{r_c} \right)^2 \frac{\xi}{\Gamma^2} \right] \right\} \approx P - P_o \quad (16a)$$

or

$$\frac{d\xi}{dt} \approx \frac{3\Gamma^2}{\pi w^3 \rho L_m} (P - P_o) \quad (16b)$$

where  $\xi \equiv \frac{x}{w}$ .

Given an arc power  $P$  delivered to the pool surface, the crown and root widths,  $r_c$  and  $r_r$ , respectively, can be estimated from equations (5) and (6) or from equations (3) and (4) with suitable truncations.  $\xi_o$ , the value of  $\xi$  at equilibrium can then be estimated from equation (13). The equilibrium value of the depression of the crown meniscus  $s_o$  can be estimated from equation (12).

If there is a fluctuation  $\Delta P$  in power, it is accompanied by a shift in the depression of the crown meniscus  $s - s_o$ , which in turn alters the voltage by changing the arc length if an automatic voltage control (AVC) is not in use or is too slow [5]. Changes in root radius alter heat loss in accord with equations (4) or (6). Hence

$$P - P_o \approx P + \eta I \frac{\partial \varepsilon}{\partial s} (s - s_o) - (P_o + \Delta P_o) \quad (17a)$$

where  $P$  = weld power input

$\eta$  = arc efficiency

$I$  = weld current

$\frac{\partial \epsilon}{\partial s}$  = voltage increment per arc length increment

$s$  = depth of crown meniscus depression

$s_0$  = initial depth of crown meniscus depression

$P_0$  = conductive heat loss at initial position

$\Delta p_0$  = change in conductive heat loss due to change in weld pool geometry

or

$$P - P_0 \approx \Delta P + \eta I \frac{\partial \epsilon}{\partial s} \left[ \frac{1}{\Gamma^2} \left( \frac{w}{r_c} \right)^2 (\xi - \xi_0) \right] w - \frac{\pi k w (T_m - T_0)}{2\Gamma^2} \left\{ \frac{\sum_{n=0}^{n=N} \frac{1}{(2n+1)^3}}{\left( \sum_{n=0}^{n=N} \frac{1}{(2n+1)} \right)^2} \right\} (\xi - \xi_0)$$

(17b)

where  $\Delta P_0 \equiv P - P_0$  = power fluctuation taken with respect to initial power input. The last term comes from equations (4) and (13c) and assumes  $r_c \ll w$ . The summation term drops from 1 at  $N=0$  to 0.22 at  $N=10$  to approximately .016 at  $N=10,000$ . This implies that adjustments in shape at the pool root have little effect upon the dissipation of heat from the weld pool. Hence we neglect this term.

$$P - P_0 \approx \Delta P + \left[ \frac{1}{\Gamma^2} \left( \frac{w}{r_c} \right)^2 \eta I \frac{\partial \epsilon}{\partial s} \right] w (\xi - \xi_0) = \Delta P + \Psi (\xi - \xi_0) \quad (17c)$$

where  $\Psi \equiv \left[ \left( \frac{w}{r_c} \right)^2 \eta I \frac{\partial \epsilon}{\partial s} \right] \frac{w}{\Gamma^2}$

Hence

$$\frac{d\xi}{dt} \approx \frac{3\Gamma^2 [\Delta P + \Psi (\xi - \xi_0)]}{\pi w^3 \rho L_m} = \frac{3\Gamma^2 \Psi \xi_0 \left[ \frac{\Delta P}{\Psi \xi_0} - 1 + \frac{\xi}{\xi_0} \right]}{\pi w^3 \rho L_m} \quad (18a)$$

$$\frac{d\zeta}{dt} \approx \frac{3\Psi\Gamma^2 \left[ \zeta - \left( 1 - \frac{\Delta P}{\Psi\xi_0} \right) \right]}{\pi w^3 \rho L_m} = \alpha_1 (\zeta - \alpha_2) \quad (18b)$$

where  $\zeta \equiv \frac{\xi}{\xi_0}$

$$\alpha_1 \equiv \frac{3\Psi\Gamma^2}{\pi w^3 \rho L_m}$$

$$\alpha_2 \equiv 1 - \frac{\Delta P}{\Psi\xi_0}$$

$\alpha_1$  and  $\alpha_3$  are constants.  $\alpha_2$  is a constant for a step power change, but otherwise is a function of time. If a step drop in power occurs and is constant, then the differential equation (18b) has a solution

$$\zeta \approx \alpha_2 + (1 - \alpha_2)e^{\alpha_1 t} = 1 + \frac{\Delta P}{\Psi\xi_0} (e^{\alpha_1 t} - 1) \quad (19)$$

The fractional change in droptthrough is  $\frac{\Delta P}{\Psi\xi_0}$  and the time constant for the change is  $\frac{1}{\alpha_1}$ .

If the power oscillates such that  $\Delta P = \Delta P_0 \sin \omega t$ , then

$$\zeta \approx 1 + \frac{\Delta P_0}{\Psi\xi_0} \left[ \frac{\left( \frac{\omega}{\alpha_1} \right) (1 - \cos \omega t) + \sin \omega t}{1 + \left( \frac{\omega}{\alpha_1} \right)^2} \right] \quad (20a)$$

such that for very slow oscillations  $\omega \ll \alpha_1$

$$\zeta \approx 1 + \frac{\Delta P_0}{\Psi\xi_0} \sin \omega t \quad (20b)$$

and for rapid oscillations  $\omega \gg \alpha_1$

$$\zeta \approx 1 + \frac{\Delta P_o}{\Psi \xi_o} \left( \frac{\alpha_1}{\omega} \right) (1 - \cos \omega t) \sim 1 \quad (20c)$$

Once penetration is lost, of course, the model changes. In this situation

$$\rho L_m \frac{d}{dt} \left[ \frac{2\pi r_c^2 w}{3} (1 + \xi) \right] \approx \Delta P + \pi k w (T_m - T_o) \{0.04\} \xi^2 \quad (21a)$$

or

$$\frac{d\xi}{dt} \approx \frac{0.06k(T_m - T_o)}{\rho L_m r_c^2} \left\{ \frac{\Delta P}{0.04\pi k w (T_m - T_o)} + \xi^2 \right\} \quad (21b)$$

where the value  $\pi k w (T_m - T_o) \{0.04\} \xi^2$  for the decrease in heat loss is an estimate from the summation of a large number of terms (10,000). It is not to be taken as precise, but neither can it be neglected in this case if an estimate of the depth of retreat of the pool root from its bottom, i.e. the lack of penetration, is to be obtained. The expression holds roughly up to  $\xi \sim 0.5$ . The value  $\Delta P$  in this case is slightly different than in the previous work; here it is, strictly speaking, the difference in power supplied by the arc to the pool from the equilibrium value at incipient penetration ( $\xi = 0$ ). The measure of incompleteness of penetration is then

$$|\xi| \approx \sqrt{\frac{-\Delta P}{0.04\pi k w (T_m - T_o)}} \quad (22)$$

## Empirical Application

A loss of penetration is known to have occurred in a 8.13mm thick plate of 2195 aluminum-lithium alloy over a travel distance of about 13 mm. The initial parameters were as follows:

$$\begin{array}{llll} w = 8.13 \text{ mm} & \rho = 2.66 \text{ gms/cc} & v = 3.18 \text{ mm/sec} & \eta \sim 0.6 \\ r_c = 6.60 \text{ mm} & \gamma \sim 900 \text{ dynes/cm} & v_w = 0 & I = 74 \text{ amps} \end{array}$$

$$r_r = 4.06 \text{ mm} \quad k \sim 100 \text{ watts/m}^2\text{K} \quad g = 980 \text{ cm}^2/\text{sec} \quad \frac{\partial \epsilon}{\partial s} \sim 1.5 \text{ volts/mm}$$

$$x = 2.54 \text{ mm} \quad L_m \sim 388 \text{ wattsec/gm} \quad T_m \sim 600 \text{ }^\circ\text{C} \quad T_o \sim 20 \text{ }^\circ\text{C}$$

Those parameters equated with an approximation sign “~” were estimated at values considered reasonable in the light of studies such as reference [5], but are imprecisely known. What follows is not intended as a precise computation, but as a demonstration of **plausibility of the theory. Typical welding situations are determined by a number of variables, not all of which are well known. Nevertheless a quantitative theory yielding approximate observed results using reasonable parameters certainly will appear promising and worth further consideration.**

From equation (13c) we find that  $\Gamma^2 = 1.25$  and  $\Phi = 3430 \text{ dynes/cm}^2$  or about 0.0034 atmospheres to satisfy static pool equilibrium. The welders use the pressure of the SPA process to attain deeper penetration than GTA would provide. Although the pressure above the weld pool is not very big, if it were reduced to zero, according to equation (13c) the droptrough  $x$  would be reduced from 2.54 mm to 2.03 mm. To get the same effect without the pressure the surface tension would have to be reduced from 900 to 344 dynes/cm. There is some uncertainty in the surface tension, but nowhere near that much.

Continuing,  $\Psi = 65.6 \text{ watts}$ . Then  $\alpha_1 = 0.0936 \text{ sec}^{-1}$  and

$$\alpha_2 = 1 - \frac{\Delta P}{20.5 \text{ watts}}. \text{ Hence}$$

$$\zeta \approx 1 + \frac{\Delta P}{20.5 \text{ watts}} \left( e^{\frac{t}{10.7 \text{ sec}}} - 1 \right) \quad (23a)$$

or, given distance  $d = vt$  along the weld bead,

$$\zeta \approx 1 + \frac{\Delta P}{20.5 \text{ watts}} \left( e^{\frac{d}{34 \text{ mm}}} - 1 \right) \quad (23b)$$

That is, given a step drop in power of 41 watts ( $\Delta P = -41 \text{ watts}$ ), which is on the order of 2% of the total weld power, penetration is lost 4.3 seconds or 13.8 mm (0.54 inches) down the weld bead. In the situation being modeled the penetration loss occurred in about a half inch. If a human has a reaction time of the order of, say, 2 seconds, a 4.3 second event such as the observed loss of penetration might well be difficult to respond to, particularly as the event would not be obvious until substantial penetration had already been lost. A 2% power loss might be expected to occur with sufficient frequency as to explain sporadic losses of penetration.

Once penetration is lost, a large upswing of the weld root can take place with a only a small reduction in power requirement. Given a 41 watt drop in power according to equation (22) equilibrium is only restored at  $\xi = 0.8$ . A somewhat more precise calculation gives  $\xi = 0.7$ . That is, a very serious loss in penetration is predicted. Equilibrium is only restored when the weld pool penetrates less than a third of the way through the plate. For the situation Table 1 below can be computed.

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**Table 1 -- Computed Effect of Power Losses**

Power Loss (watts)	Loss of Penetration Begins in		Maximum Penetration Loss (Equation 22) (%)
	Time (sec)	Distance (mm)	
1	33	104	13
5	17	55	29
10	12	38	40
20	7.5	24	58
30	5.6	18	71
40	4.4	14	82

The computed times and distances for loss of penetration seem to be in line with observations.

The computed maximum penetration loss seems high, although penetration losses as great as 30% of thickness are sometimes seen. The computed value should be taken as an upper bound. Normally when penetration losses occur a welder becomes aware that penetration is being lost and begins to compensate before the loss actually occurs.

### Power Fluctuations

If we examine a typical weld of the sort with which we have been concerned, we find variations in crown width on the order of 2 to 3%. If the weld speed is slow and the root width is wide enough to treat the weld pool as a cylinder leaking heat radially from a weld of diameter  $d$  to some ambient diameter  $d_o$ , then the power change  $\Delta P$  associated with the change in diameter  $\Delta d$  can be estimated. It is assumed that  $\Delta d \ll d$ .

$$\Delta P \sim 2\pi kw(T_m - T_o) \left\{ \frac{1}{\ln\left(\frac{d_o}{d + \Delta d}\right)} - \frac{1}{\ln\left(\frac{d_o}{d}\right)} \right\} \approx 2\pi kw(T_m - T_o) \left\{ \frac{\frac{\Delta d}{d}}{\left[\ln\left(\frac{d_o}{d}\right)\right]^2} \right\} \quad (24)$$

If  $d$  is around 1 centimeter and  $d_o$ , 20 centimeters, then the power fluctuations  $\Delta P$  are on the order of 7 or 8 watts. The variations are sporadic, but tend to repeat with a periodicity on the order of 120 mm, say  $\Delta P \sim (7 \text{ watts}) \sin\left[\left(0.2 \text{ sec}^{-1}\right)t\right]$ . From equation (20a) it can be shown that

$$1 + \frac{\Delta P_o}{\Psi \xi_o} \left\{ \frac{\left( \frac{\omega}{\alpha_1} \right) - \sqrt{1 + \left( \frac{\omega}{\alpha_1} \right)^2}}{1 + \left( \frac{\omega}{\alpha_1} \right)^2} \right\} \leq \zeta \leq 1 + \frac{\Delta P_o}{\Psi \xi_o} \left\{ \frac{\left( \frac{\omega}{\alpha_1} \right) + \sqrt{1 + \left( \frac{\omega}{\alpha_1} \right)^2}}{1 + \left( \frac{\omega}{\alpha_1} \right)^2} \right\} \quad (25)$$

Applying a 7 watt fluctuation with  $\omega = 0.2 \text{ sec}^{-1}$  to the case discussed above we find that  $\zeta$  fluctuates with variation of  $\pm 0.34$ , not enough to lose penetration. Observations of the sample look more like  $\pm 0.08$  rather than  $\pm 0.34$ . But the data is too scattered to draw any conclusion except that the above analysis is not excluded by present observations.

The above analysis would show loss of penetration if the power fluctuation were increased to 21 watts, although the observations suggest that the analysis may substantially underestimate the power fluctuation requirement for loss of penetration.

What could cause a substantial power drop or fluctuation? Several candidates come to mind:

1. Diversion of the heat of the arc by an air current. This is thought to be unlikely as a cause of sporadic loss of penetration as it would be visible to the welder, who would notice a correlation between arc movement or fluctuations and loss of penetration.

2. Alteration of water cooling of the torch orifice. Increasing the temperature of the torch orifice is not expected to have a large effect on the arc itself, but should promote more rapid deterioration of the orifice passages. A sudden change in orifice geometry could alter arc characteristics. But one would expect this correlation would be noticed by the welder.

3. Electrode deterioration. Burnback of the tungsten electrode of a plasma torch would increase effective arc length and thereby voltage; if this were to occur with automatic voltage control (AVC) in operation, however, it would be compensated. Burnback would also increase the flow area for the plasma gas in the torch. Increased plasma gas flow draws more voltage to maintain conductive temperature. Higher flow velocities increase convective heat transfer. Thus one might expect a power increment, even if the voltage rise is compensated by the AVC. It could occur suddenly if a piece of the electrode were to break off suddenly. However, this effect would most likely cause an increase in penetration, not a decrease, and, further, it would be accompanied by tungsten inclusions in the weld metal.

For SPA operation the electrode protrudes out of the plasma gas orifice. Electrode deterioration might cause an increase in arc length, which the AVC would compensate. A significant effect on the plasma gas flow would not be anticipated for SPA.

4. Ground resistance variations. If the AVC fixes the torch voltage and if the torch voltage drop is divided over the arc and the ground, then when the ground resistance rises the arc voltage drops. The ground resistance presumably is distributed over a fairly wide area and has little heating effect on the weld pool. Thus an increase in ground resistance causes a drop in power delivered to the weld pool. Surface contact resistance is sensitive to local pressure or surface contaminant variations. A  $\pm 7$  watt power variation at 74 amps current implies a  $\pm 0.1$  volt variation and a resistance variation of  $\pm 0.0013$  ohms.

Instances of loss of penetration have been associated with thermal buckling of a plate away from a backing surface. At the time it was remarked upon because the loss of contact with the backing surface was expected to increase, not decrease penetration since the loss of contact reduced thermal conductive losses. However, if the ground resistance increase due to the loss of contact predominates over the reduction in heat conduction loss, the observed loss of penetration could be explained.

Pending further study ground resistance variations appears to be the best candidate cause for power variations capable of causing loss of penetration.

## Conclusions and Recommendations

A tentative equation of motion for the droptthrough distance (x) at the root of a penetrating weld pool and for the lack of penetration (-x) at the root of a non-penetrating weld pool has been derived for the flat position.

The droptthrough and lack of penetration are metastable at small values with respect to the plate thickness, i.e. close to incipient penetration. A small reduction in power to the pool will cause the droptthrough to decrease progressively until penetration is lost. The time constant  $\tau$  for this decrease is approximately

$$\tau \approx \frac{\pi r_c^2 \rho L_m}{3\eta I \frac{\partial \epsilon}{\partial s}}, \quad (26)$$

that is, a ratio between a thermal inertia term dependent on the size of the pool and the latent heat of the metal and a power driving term dependent upon the arc efficiency, weld current, and the change in voltage when the arc is elongated. Big pools and small weld currents make for a slow response, other things being equal.

But the actual time  $\tau_o$  to lose penetration depends upon the size of the power disturbance.

$$\tau_o \approx \tau \ln \left\{ 1 + \frac{4\eta I \frac{\partial \epsilon}{\partial s} x_o}{\rho g r_c^2 \left[ 1 + \frac{12 a_w v_w}{\pi r_c v} + \frac{\Phi}{\rho g w} \right] \Delta P} \right\} \quad (27)$$

and if the term second in brackets is small compared to one,

$$\tau_o \sim \frac{4\pi}{3} \frac{\gamma x_o}{g \left[ 1 + \frac{12 a_w v_w}{\pi r_c v} + \frac{\Phi}{\rho g w} \right] \Delta P}. \quad (28)$$

High surface tension and initial droptthrough promote long times before penetration is lost. The magnitude of the pressure disturbance and the pressure on top of the pool speed up the process toward loss of penetration.

Processes differ with respect to stability. The SPA process with higher pressure over the weld pool is, in this analysis, more prone to loss of penetration than the GTA process.

If a step power change occurs and remains uncompensated for a long enough time penetration can be lost. But if the rises follow soon enough after the drops, penetration loss can be avoided. The effect of the frequency of a sinusoidal power fluctuation is estimated in equation 25.

Metals, too, differ with respect to stability. 2195 aluminum-lithium alloy with a lower surface tension is, in this analysis, more prone to loss of penetration than 2219 aluminum alloy.

Ground resistance variations are a possible cause of power fluctuations leading to loss of penetration. It is estimated that ground resistance variations on the order of a few milliohms could produce power fluctuations sufficient to produce sporadic losses in penetration.

The above conclusions are tentative. It is recommended that this work be followed up by experimental study to evaluate the conclusions and, pending confirmation, to consider in its light the optimum operational parameters and control system to prevent loss of penetration during flat position welding.

### *Acknowledgements*

The authors would like thank J. P. Norris of Lockheed Martin Space Systems for allowing them to draw upon his wide and first-hand experience with SPA welding of 2195 aluminum-lithium alloy.

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